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14. ABSTRACT The attached document is the final report for AFOSR grant no. F49620-01-1-0321. The originally proposed tasks were addressed more or less completely in the course of the funded work. The following research milestones were reached: 1. The statistical information content of prior knowledge in the form of support was assessed theoretically and via simulation of speckle interferometric imaging; 2. A comparison of blind deconvolution techniques using Shannon mutual information; 3. A Fisher information based study of phase-diversity speckle method, including the optimal choice and strength of diversity phase in the second channel; 4. A Fisher information based optimization of wavefront encoded imaging systems; 5. The use of successfully transmitted statistical information as a performance metric for stopping iterative image restoration algorithms like the Richardson-Lucy algorithm; 6. Clarification of the fundamental nature of Fisher information; and 7. A derivation of sum rules that connect information in the physical and Fourier domains.

15. SUBJECT TERMS
Fisher information, statistical information, image processing, optimization, integrated optical-digital imaging system, support constraint, phase diverse speckle imaging

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Final Performance Report for Grant F49620-01-1-0321

1. Status of Effort

The three-year effort led to a number of important research milestones in the topic of information theory and its application to image formation, detection, and processing. Essentially all of the objectives of the original proposal were accomplished, and additionally some new directions of information-theoretic imaging research were explored.

2. Accomplishments and New Findings

Described below are highlights of research and their significance/relevance to the field of imaging and the scientific, industrial, and military community.

a. Noise reduction and information gain from prior knowledge of object support

Most image processing algorithms implement prior knowledge about the object in one form or another. Thus, for example, the two workhorses of astronomical image processing, namely the maximum-entropy method (MEM) and CLEAN algorithms, each assume a certain object structure, a diffuse object and an object consisting of point sources, respectively. A very useful piece of prior knowledge that can lead to improved processing is the support of the object intensity distribution, sometimes available from either low-resolution images or other kinds of reconnaisance.

A precise knowledge of object support can reduce noise in two ways: First, because the object is known not to extend beyond the support boundary, any observed image data with intensity well outside the support bound-

ary must be pure noise, which can then be trivially eliminated. Second, the imposition of support in the image domain via a multiplication of the obeserved image data by a support function that is 1 within the support and 0 outside means that the spectrum of the support-constrained image is a convolution of the unconstrained image spectrum and the support-function spectrum. Such a convolution will lead to a transport of noise across spatial frequencies, which can be used to reduce the noise within the support boundary as well via a noise-reduction algorithm first proposed by Matson and Tyler.

Under the present AFOSR grant, the present PI (Prasad) greatly clarified the detailed nature of this noise transport. The transport of noise occurs in this model by a combination of ballistic motion, or drift, and diffusive spreading described an infinite hierarchy of generalized diffusion constants. For an inversion-symmetric support, it was shown that the drift is absent and noise transport is exclusively diffusive. For this case, an analytical expression was derived for the reduction of noise such diffusive spreading in the spatial-frequency plane can facilitate, when a circular support of arbitrary size is employed. Details may be found in Ref. [3] which was supported by a precursor AFOSR grant.

An alternative but presumably entirely equivalent viewpoint is to consider how the information content of an image improves with the application of *a priori* constraints like the finiteness of support. This picture can be accorded quantitative meaning via the concept of Shannon's statistical entropy [1, 2] whereby a statistical set of representative objects, rather than a single object, is processed by a finite-bandwidth imaging system in the presence of noise. Image reconstruction under noisy conditions reduces the amount of object information that can be passed by the imaging system, but that reduction is expected to be smaller when some *a priori* information about the objects like finite support can be implemented in the reconstruction algorithm. The influence of an *a priori* constraint on the degree of reduction of information can thus be assessed for the object set chosen. Obviously it would also be possible to estimate how meaningful different constraints would be for different object sets and under different operating conditions. A preliminary analysis of this information-theoretic viewpoint for the support constraint was given in two earlier papers by the author [4] and David Tyler [5] under support from a previous AFOSR grant.

b. Statistical information as a performance metric for iterative image processing

The value of iterative image processing has been well established in generating images that display a delicate balance between resolution, noise, and dynamic range. The most serious problem facing image processing, whether iterative or not, however, is the matter of choosing one or more regularization parameters that determine this delicate balance in the restored image. A number of approaches have been adopted to regularize the problem. These approaches range from added damping to prevent excessive noise amplification to restoring images on a reduced-resolution template (the method of sieves) to the method of cross-validation to penalized restoration.

An approach that the PI has suggested in work supported by the AFOSR grant is to use statistical information as a regularizer and restoration metric. We have carried out a statistical-information based analysis [6] of the popular Richardson-Lucy iterative deblurring algorithm after clarifying the detailed nature of noise amplification and resolution recovery as the algorithm iterates. Monitoring the information content of the reconstructed image furnishes an alternative criterion for assessing and stopping such an iterative algorithm. It is straightforward to implement prior knowledge and other conditioning tools in this statistical approach. Both Gaussian detector noise and Poisson shot noise were considered in this work, and similar information peaks were seen as functions of iteration number in all spatial-spectral bands over which information was monitored. It is conjectured that information is maxmimized when the above-mentioned delicate balance between the various indicators of good image quality has been reached. This approach also allows for a comparison of various iterative methods on the same object classes and given system operating conditions, as we demonstrated in concurrent work [7].

This work has been greatly generalized and expanded by the Ph.D. dissertation work of Dr. Douglas Hope [8] under the PI's supervision. He has applied the information theoretic characterization to both filled-aperture and sparse-array interferometric imaging as well as speckle interferometry, and has studied the detailed relation between the traditional noise-based analysis and our new information-based analysis of these imaging approaches. Thanks to these advances, principally enabled by the AFOSR grant support, information based assessments of imaging systems seem to be gaining popularity, at least in the DoD community. An emerging project called Enhancement via Information Theoretic Analysis (EVITA), an AFRL-Boeing LTS joint activity under which the University of New Mexico is also

supported by a subcontract, is a direct result of our successful information-theoretic imaging researches.

c. Fisher information with respect to cumulants

In our AFOSR-grant funded researches, we have considered both statistical information, as introduced by Shannon, and Fisher information, a statistical-estimation-theoretic information measure. The inverse of Fisher information (FI) provides the lowest possible theoretical bound on the error of estimation of a parameter from statistical data. Specifically, the FI is a direct measure of the sensitivity of statistical data, via their probability distribution (PD), on the parameter to be estimated from those data.

The nature of FI, introduced nearly eighty years ago [9] and applied to a large variety of problems in all domains of statistical analysis during this time, is well understood. Yet, in a rather seminal work [11], the PI in collaboration with a very bright undergraduate, Nicolas Menicucci, showed that the concept of FI, which is a functional of the PD of the data, can be utilized in estimating the PD itself. Any PD is characterized by one or more parameters (such as the mean and variance) as well as a functional form (e.g., Gaussian, Poisson, binomial, etc), and estimating these parameters and the functional form is then equivalent to estimating the PD itself. The authors showed that by parameterizing the PD in terms of all its cumulants, one has a direct handle on the explicit parameters as well as the functional form of the PD. The estimation of the PD then reduces to estimating the cumulants of the distribution, relative to which the FI can be written down. The FI with respect to cumulants is an infinite-dimensional matrix, but the authors showed that the form of all the matrix elements is rather simple and analytically expressible in closed form. The simple analytical form can be used to motivate a number of generating functions for the FI and its inverse matrix, the diagonal elements of the latter providing the bounds, the so-called Cramér-Rao lower bounds, on the variance of the estimators for the cumulants. These bounds, taken together, may be regarded as determining the best possible accuracy with which the PD itself can be estimated, since the PD is a unique function of its cumulants.

There is an important possible application of this work to imaging that we are currently exploring. Note that the spatial distribution of intensity in any image may be regarded as a PD, for image intensities are always nonnegative and the total image flux is always finite and thus one can always normalize an image distribution so that all its pixel intensities add to 1 just as the probabilities in a PD. Image restoration is then equivalent formally to

estimating a PD, which can be done iteratively, starting from the observed (but normalized) image data that can hopefully be refined iteratively with improving knowledge of the equivalent PD and thus, via our work, of the accuracy with which the PD can be estimated at a specific iteration number. Just how the iterations refine the estimation process is currently under study.

d. Fisher-information based optimization of phase diversity blind deconvolution

FI can be used in much the same way as Shannon information to characterize the quality of image restoration. There is, however, a qualitative difference of interpretation: An FI based metric yields the goodness of estimation of object parameters, while any Shannon information based metric is a measure of the goodness of discrimination between object scenes belonging to a statistical ensemble of object scenes. Regardless of this qualitative difference, both kinds of metrics can serve as excellent objective measures of image quality.

Phase diversity speckle (PDS) imaging is a type of blind deconvolution algorithm for image restoration from data that consist of multiple images collected by a ground-based telescope under the same but unknown atmospheric (or speckle) conditions. The success of PDS image restoration has to do with the fact that the object being reconstructed as well as the atmospheric turbulence parameters, although not known *a priori*, are nevertheless the same across the multiple image channels. Coupled with the positivity of the image and a statistical knowledge of turbulence, the determination of the object becomes a reliably unique process, provided enough diversity ("differentness") exists across the multiple channels. In conventional PDS system, there are two image channels, one corresponding to an in-focus image and another corresponding to a defocused image. Basically, light from the source is split in two equal sub-beams which are then imaged on to two cameras, one of which is in perfect focus and the other slightly out of focus. The diversity phase in this case is the defocus induced quadratic phase profile across the pupil in the second imaging channel.

That the defocus cannot be too small or too large for optimum performance of the PDS system can be argued as follows. If the defocus were too small, the defocused image would be essentially indistinguishable from the in-focus image, adding little information to the latter, while for too large a defocus, the defocused image would be too fuzzy and faint, and thus too noisy to carry much useful additional information about the object. It is clear that optimum performance is obtained when the defocus is just right

in the sense that the defocused channel adds maximum information to that present in the in-focus image. A measure of added information is conditional FI, which may be defined as the difference between the FI of the two image channels taken together and the Fi in the in-focus image alone. Note that since the concept of Fisher information is defined only relative to certain parameters that are being estimated, the matter of optimization is also a subjective one, depending on the set of estimation parameters. The dependence of optimum performance on the imaging task ("which parameters are to be estimated?") is a fundamental element of all information theoretic considerations.

Previous work by other researchers was devoted to addressing this optimization question relative to the task of estimating the random pupil phase parameters that are realized frame by frame under a given turbulence condition. The PI's work under the grant was instead directed to the matter of estimating the object itself, a task that can be mathematically cast as one of estimating, for instance, the object spectrum. The FI matrix defined relative to the object spectral parameters was evaluated under the assumption that the turbulence induced phase degradations are sufficiently strong, $D/r_0 >> 1$, for which the image spectra approximately obey Gaussian statistics whenever the light levels are sufficiently bright so any shot noise can be ignored altogether and only the Gaussian noise of CCD readout is of any consequence. These somewhat restrictive conditions required for Gaussian statistics apply nevertheless to situations of practical interest, e.g., low-contrast images with high bias, fast thermal imaging with intrinsically bright sources, etc.

Under these conditions, the following expression was obtained for the joint FI in the two channels[12, 13]:

$$\begin{aligned}
J^{(0,1)}[\tilde{f}(\vec{u}_1), \tilde{f}(\vec{u}_2)] &\equiv \left\langle \frac{\delta \ln \tilde{P}^{(0,1)}(\tilde{g}_0, \tilde{g}_1)}{\delta \tilde{f}^*(\vec{u}_1)} \frac{\delta \ln \tilde{P}^{(0,1)}(\tilde{g}_0, \tilde{g}_1)}{\delta \tilde{f}(\vec{u}_2)} \right\rangle \\
&= \left\{ \sum_{i,j} \left\langle \tilde{h}_i(\vec{u}_1) \right\rangle \tilde{k}_{ij}^{(g)*}(\vec{u}_1) \left\langle \tilde{h}_j^*(\vec{u}_1) \right\rangle \right. \\
&+ \left. \delta(0) |\tilde{f}(\vec{u}_1)|^2 \left[|\alpha(\vec{u}_1)|^2 - \frac{2 \det \tilde{c}^{(h)}(\vec{u}_1)}{\det \tilde{c}^{(g)}(\vec{u}_1)} \right] \right\} \\
&\times \delta(\vec{u}_1 - \vec{u}_2), \qquad (1)
\end{aligned}$$

where the function $\alpha(\vec{u})$ is defined as

$$\alpha(\vec{u}) = \frac{2|\tilde{f}(\vec{u})|^2 \det \tilde{c}^{(h)}(\vec{u}) + [\sigma_0^2 \tilde{c}_{11}^{(h)}(\vec{u}) + \sigma_1^2 \tilde{c}_{00}^{(h)}(\vec{u})]}{\det \tilde{c}^{(g)}(\vec{u})} \qquad (2)$$

and $\tilde{k}^{(g)}$ denotes the inverse of the 2×2 image-spectrum covariance matrix $\tilde{c}^{(g)}$ at a given spatial frequency. The symbol σ_i^2 denotes the detector noise variance at each pixel in the ith channel. A similar but simpler expression may be written down for the FI in the in-focus image plane alone,

$$J^{(0)}[\tilde{f}(\vec{u}_1), \tilde{f}(\vec{u}_2)] = \delta(\vec{u}_1 - \vec{u}_2) \left[\frac{|\langle \tilde{h}_0(\vec{u}_1) \rangle|^2}{\tilde{c}_{00}^{(g)}(\vec{u}_1)} + \delta(0) |\tilde{f}(\vec{u}_1)|^2 |\beta_0(\vec{u}_1)|^2 \right], \quad (3)$$

where the function $\beta_0(\vec{u})$ is defined as

$$\beta_0(\vec{u}) = \frac{\tilde{c}_{00}^{(h)}(\vec{u})}{\tilde{c}_{00}^{(g)}(\vec{u})}. \quad (4)$$

The first term on the right-hand side in Eqs. (1) and (3) represents the FI about the object that is contained in the two *mean* images and the in-focus *mean* image, respectively, while the remaining terms represent the contribution made by the information present in the *fluctuations* of the image spectrum. For any speckle based system, it is well known that the latter information extends out to the diffraction cut-off u_c,[15] while the former is negligible for frequencies that exceed the much smaller atmospheric cut-off frequency u_a.

These expressions were graphically displayed and discussed in Ref.[12, 13], and it was determined that a defocus-dependent quadratic phase between 3-7 radians at the edge of the pupil in the defocused channel was optimal in extracting maximum possible source information in the limit of an unresolved point source. These numbers agree with the optimal values of defocus phase corresponding to the optimum estimation of random pupil phase parameters under a wide range of operating conditions, as shown by previous researchers. Our results thus give us much confidence that the optimum defocus value is optimized at once for both object and pupil phase estimation tasks of a conventional two-channel PDS imaging system.

Our general approach based on FI can be extended to a more comprehensive set of optimization questions for PDS imaging, namely how many channels and what known phase perturbation beyond defocus might be the most optimal under a given set of operating conditions. Our preliminary work [14] has indicated that the form of the pupil phase in the diversity channel may not be very critical in the context of PDS imaging. Recent studies [16, 17] in extended focus imaging systems, however, have established the value of carefully engineered pupil-phase profiles in improving the

quality of restored images, and such pupil phases may be important in future generations of PDS imaging systems as well. In many of the general derivations presented here, no specific use is made of the fact that there are only two channels and that the diversity phase is a pure defocus. The present theoretical framework can thus be readily adapted not just to more general forms of PDS imaging but even to the most general of optical-digital imaging systems.

e. Fisher-information based characterizations of the focus extension problem

By suitably phase-encoding optical images in the pupil plane and then digitally restoring them, one can greatly improve their quality. The use of a cubic phase mask originated by Dowski and Cathey [16] to enhance the depth of focus in the images of 3-d scenes is a classic example of this powerful approach.

Two years ago, working in collaboration with a team of researchers at the Wake Forest University led by Professor Robert Plemmons, the co-PI of the AFOSR grant, the PI proposed a radical generalization of this approach that is based on the theory of mathematical optimization. In our approach, which we call pupil-phase engineering, we first expand the pupil phase function in a set of basis functions, such as the orthogonal Zernike polynomials or the ordinary nonorthogonal (but linearly independent) polynomials. We then choose the set of values of the coefficients of such expansions by imposing the requirement that there be both maximum possible invariance of imaging to the depth coordinate as well as maximum possible digital restorabilty of the phase-encoded, intermediate image. This defines an optimization problem to which modern tools of optimization theory can be readily applied. Our approach is sufficiently general in that, as we have recently shown [18], it can be used to compensate for undetermined types and strengths of imaging system aberrations as well. It thus ensures that the encoded image will be formed under a nearly shift-invariant imaging condition, which can then be digitally restored to a high overall quality nearly free from the aberrations and limited depth of focus of a traditional imaging system.

A very useful measure of sensitivity of images to focus and aberrations related errors is based on the concept of Fisher information. In order to demonstrate the validity of our general approach, we obtained results of computer simulations that include the limitations imposed by detector. Fisher information also provides a very useful physical characterization of the tradeoff between longitudinal (or focus) blur and transverse blur (of the phase-

encoded blurry image). It is this trade-off that lies at the heart of our PPE approach to curb focus blur.

A number of papers [19, 20, 17, 21, 22] that cite AFOSR grant support have been – and continue to be – published over the past two years. They have firmly established the effectiveness and superiority of the optimization approach when compared to the original, somewhat simplistic cubic-mask approach. Our PPE approach – and its information theoretic characterization – provide the best framework in which to discuss the more general problem of integrated imaging systems which are optimized against a number of system performance trade-offs, not just the longitudinal vs. transverse trade-off we mentioned earlier in the context of focus extension.

f. Information theoretic sum rules in the physical and Fourier domains

Physical symmetries and conservation laws provide the most fundamental basis for all valid physical theories. Notable among such conservation laws are energy, linear momentum, angular momentum, charge, and the invariance of physical laws under general coordinate frame transformations. In the context of signal and image processing, an important conserved quantity is the total noise power which is invariant under Fourier transformations, making it possible to compute and interpret it in the physical or Fourier domain with equal ease and convenience.

Information theory [1] provides another important ingredient of any description of modern signal processing, computation, and communication systems. Over the past fifty years, our familiarity with information has grown to the extent that we have come to regard it as being on par with other fundamental entities like energy, power, etc. In fact, serious attempts [23, 24] have been recently made to elevate information theory even further, by exploring whether it can serve as an essential construct for all physical laws of nature.

In a paper recently submitted for publication [25], we have derived certain sum rules for Fisher information and quantities directly related to it. These sum rules govern the conservation of integrated information and related quantities under transformations of the Fourier type. They serve to illuminate the fundamental meaning assigned to Fisher and other types of information as practical measures of information and knowledge. The context in which we derived our sum rules is imaging, but the results are general and apply to any kind of signal one can imagine.

The results of this paper demonstrate that for both unbiased and biased

estimation problems, there are conservation laws that govern the transformation between physical and Fourier domains. These laws relate to ordinary and uniform Cramér-Rao bounds in their sum form, as shown in this paper.

g. Summary and Conclusions

In the three-year grant period, a number of information theoretic characterizations and elaborations of imaging systems were successfully pursued, leading to some seminal results. Our grant funded researches have clarified the nature of Fisher information (Secs. 3 and 6); established the value of using information theory to characterize the absolute and relative performances of various image processing algorithms (Sec. 2); helped us quantify the degree of noise reduction and information gain resulting from application of prior knowledge, such as support (Sec. 1); demonstrated the usefulness of Fisher information in assessing the degree of invariance in focus-extension and/or aberration-control problems (Sec. 5); and illustrated the pre-eminence of information as a comprehensive metric for assessing and optimizing the performance of integrated imaging systems, like phase-diverse speckle imaging (Sec. 4). Unlike the traditional noise-based performance analyses, an information theoretic metric of performance encapsulates all measures of image quality, including sensitivity, resolution, and dynamic range, in a single task-dependent quantity. Information theory provides a physically insightful approach to discussing various system trade-offs that are critical for optimizing the performance of modern imaging systems.

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3. Personnel Supported

A number of research personnel at the University of New Mexico and Wake Forest University were supported under the grant funding:

- Faculty: Sudhakar Prasad (PI) and Robert Plemmons (Co-PI)
- Post-Doctoral Fellows: None
- Graduate Students: Douglas Hope, J. Douglas Hague, and Marcelo Vogel.
- Undergraduate Students: Nicolas Menicucci.

4. Publications

A total of 12 papers, including 6 peer-reviewed papers, have been either already published (8) or accepted for publication (2) or submitted for publication (2). All of the peer-reviewed publications are listed below:

- S. Prasad, "Statistical Information Based Performance Criteria for Lucy Richardson Image Deblurring," J. Opt. Soc. Am. A. **19**, 1286-1296 (2002).

- S. Prasad and N. Menicucci, "Fisher Information with respect to Cumulants," IEEE Trans. Inform. Theory **50**, 638-642 (2004).
- S. Prasad, "Information Optimized Phase Diversity Speckle Imaging," Opt. Lett. **29**, 563-565 (2004).
- S. Prasad, "Fisher Information Based Analysis of a Phase Diversity Speckle Imaging System," J. Opt. Soc. Am. A, to appear Nov. 2004.
- S. Prasad, T. Torgersen, V. P. Pauca, R. Plemmons, and J. van der Gracht, "High-Resolution Imaging Using Integrated Optical Systems," Int. J. Imaging Syst. Technolog., in press (2004).
- S. Prasad, "Integrated Information and Noise in the Physical and Fourier Domains," submitted to IEEE Transactions on Signal Processing, August 2004.

5. Interactions/Transitions

a. Presentations

A total of 16 conference presentations, colloquia, and seminars based on the research conducted under the grant were made.

b. Consultative/Advisory Functions

The PI served on a DARPA/DSRC panel considering frontier research directions in the area of information and photonics. The brainstorming session was held June 24, 2004 at the Booz Allen Hamilton facility in Arlington, VA, and involved researchers and scientists from DARPA, DSRC, academia (including Stanford, Rochester, UNM, Mayo Clinic, etc) and industry.

c. Transitions

A potential technology transition exists in the area of pupil-phase engineering, where we have been in consultation with the MOSAIC facility at Oceanit, Inc., Maui, HI to explore the fabrication of pupil-phase elements that have been optimized according to our theoretical work, described in Sec. 2.e. If approved, the cost of fabrication will be borne by an Army Research Office grant to Wake Forest University.

6. Inventions/Patent Disclosures

None.

7. Honors/Awards

The PI has been nominated to become an Optical Society of America Fellow. The final decision regarding the award will be made by the end of Fall 2004.